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Preliminary Navigation Accuracy Analysis for the TDRSS Onboard Navigation System (TONS) Experiment on EP/EUVE*

C. J. Gramling
GODDARD SPACE FLIGHT CENTER (GSFC)

A. C. Long, T. Lee, N. A. Ottenstein, and M. V. Samii
COMPUTER SCIENCES CORPORATION (CSC)

ABSTRACT

A Tracking and Data Relay Satellite System (TDRSS) Onboard Navigation System (TONS) is currently being developed by the National Aeronautics and Space Administration (NASA) to provide a high-accuracy autonomous navigation capability for users of TDRSS and its successor, the Advanced TDRSS (ATDRSS). The fully autonomous user onboard navigation system will support orbit determination, time determination, and frequency determination, based on observation of a continuously available, unscheduled navigation beacon signal. A TONS experiment will be performed in conjunction with the Explorer Platform (EP)/Extreme Ultraviolet Explorer (EUVE) mission to flight qualify TONS Block I.

This paper presents an overview of TONS and a preliminary analysis of the navigation accuracy anticipated for the TONS experiment. Descriptions of the TONS experiment and the associated navigation objectives, as well as a description of the onboard navigation algorithms, are provided. The accuracy of the selected algorithms is evaluated based on the processing of "realistic" simulated TDRSS one-way forward-link Doppler measurements. This paper discusses the analysis process and presents the associated navigation accuracy results.

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1. INTRODUCTION

The Tracking and Data Relay Satellite System (TDRSS) and its successor, the Advanced TDRSS (ATDRSS), will provide future National Aeronautics and Space Administration (NASA) low Earth-orbiting spacecraft with telemetry, command, and tracking services. These user spacecraft require position, time, and frequency data to maintain their operational health and safety and to annotate their science data. Currently, TDRSS supports user spacecraft orbit, time, and frequency determination through ground-based extraction and processing of range and Doppler tracking measurements. TDRSS provides both two-way and one-way return-link scheduled tracking services for equipped users. Proposed enhancements to TDRSS/ATDRSS will provide unscheduled forward-link beacon tracking services.

The capability to support user spacecraft orbit and frequency determination solely by ground-based processing of TDRSS one-way return-link Doppler measurements increases TDRSS availability by reducing scheduled resource requirements and alleviates some operational complexity. This capability is achieved by augmenting the second-generation TDRSS user transponder with an external ultrastable oscillator (USO). This tracking configuration has been flight demonstrated onboard the Cosmic Background Explorer (COBE) mission (Reference 1); and, as a result, the decision was made to use one-way return-link Doppler operationally to support COBE. In 1992, one-way return-link Doppler tracking will also be used to support the Ocean Topography Experiment (TOPEX) mission.

A TDRSS Onboard Navigation System (TONS) is being developed by NASA to provide spacecraft autonomous navigation products for low Earth-orbiting spacecraft via the onboard extraction of highly accurate tracking measurements. TONS will decrease the user's reliance on TDRSS ground operations and scheduled TDRSS resources while at the same time achieving onboard accuracy commensurate with that achievable using the Global Positioning System (GPS). Various levels of upgrades to user spacecraft and TDRSS capabilities will allow corresponding increases in the degree of user autonomy, navigation services, and failure modes. The objective is to develop a fully autonomous user navigation system that supports onboard orbit determination, time determination, and frequency determination, based on observation of a continuously available, unscheduled navigation beacon signal.

TONS is being developed in three stages. The first stage is the TONS experiment, which is being performed in conjunction with the Extreme Ultraviolet Explorer (EUVE) mission, hosted on the Explorer Platform (EP). The EUVE TONS experiment provides an opportunity to flight qualify TONS by processing Doppler data extracted on-orbit and telemetered to the ground in a flight-emulation experiment. On future missions, TONS Block I and TONS Block II will provide onboard user navigation. TONS Block I, the second stage, will use Doppler data derived from scheduled forward-link S-band services to provide onboard orbit and frequency determination. If implemented, TONS Block II, the third stage, will use Doppler and pseudorange data derived from a continuous, unscheduled forward-link S-band beacon service to provide onboard orbit, time, and frequency determination. The TONS Block I and TONS Block II systems are discussed in detail in Reference 2.

Sections 2 and 3 of this paper provide an overview of the TONS experiment and a description of the TONS Flight Software. Section 4 describes the navigation analysis method, and

Section 5 presents the results of a preliminary analysis of the TONS navigation accuracy under the expected operational conditions of the EP/EUVE mission. Remarks and conclusions are provided in Sections 6 and 7, respectively.

2. TONS EXPERIMENT ON EP/EUVE

The TONS experiment requires a forward-link scheduled reference signal from a Tracking and Data Relay Satellite (TDRS), a Doppler extractor (DE) card in the user transponder, a USO, signal acquisition software onboard the user spacecraft, and a ground-based navigation processor. The primary objectives of the TONS experiment follow:

- To flight demonstrate the performance of the Doppler extractor card in the second-generation TDRSS user transponder to extract high-precision Doppler measurements from forward-link S-band signals
- To flight qualify key components of an autonomous navigation processing system that uses the extracted Doppler measurements
- To flight demonstrate onboard Doppler compensation (OBDC) for supporting signal acquisition using onboard software and commands
- To develop and evaluate flight software in a ground-based flight emulation environment

Successful completion of the TONS experiment will demonstrate the flight readiness of the TONS Block I system.

The TONS experiment involves both flight systems onboard EP/EUVE and ground systems for experiment data processing and performance evaluation. Figure 1 provides an overview of the TONS experiment configuration. The flight and ground segments of this configuration are described in detail in References 3 through 6.

2.1 SPACE SEGMENT

To support the experiment, EP/EUVE will accommodate the components to perform the onboard extraction of one-way forward-link TDRSS Doppler measurements and telemeter these data to the ground. The TONS experiment space-based components include an external USO interfaced to the EP second-generation TDRSS user transponder that includes a DE card, Transponder-B. For control purposes and telemetry data collection, the USO and transponder are also interfaced to the onboard computer system (OBC), a NASA Standard Spacecraft Computer (NSSC)-I, through a remote interface unit (RIU). The USO provides a stable frequency reference to Transponder-B. A numerically controlled oscillator (NCO) in the transponder's carrier tracking loop generates internal frequency control words (FCWs) to maintain lock with the received TDRSS forward-link signal. The DE accumulates these internal FCWs. A Doppler count measurement is obtained by sampling the DE 40-bit accumulator every 10.24 seconds. This Doppler extraction capability is discussed in detail in Reference 7.

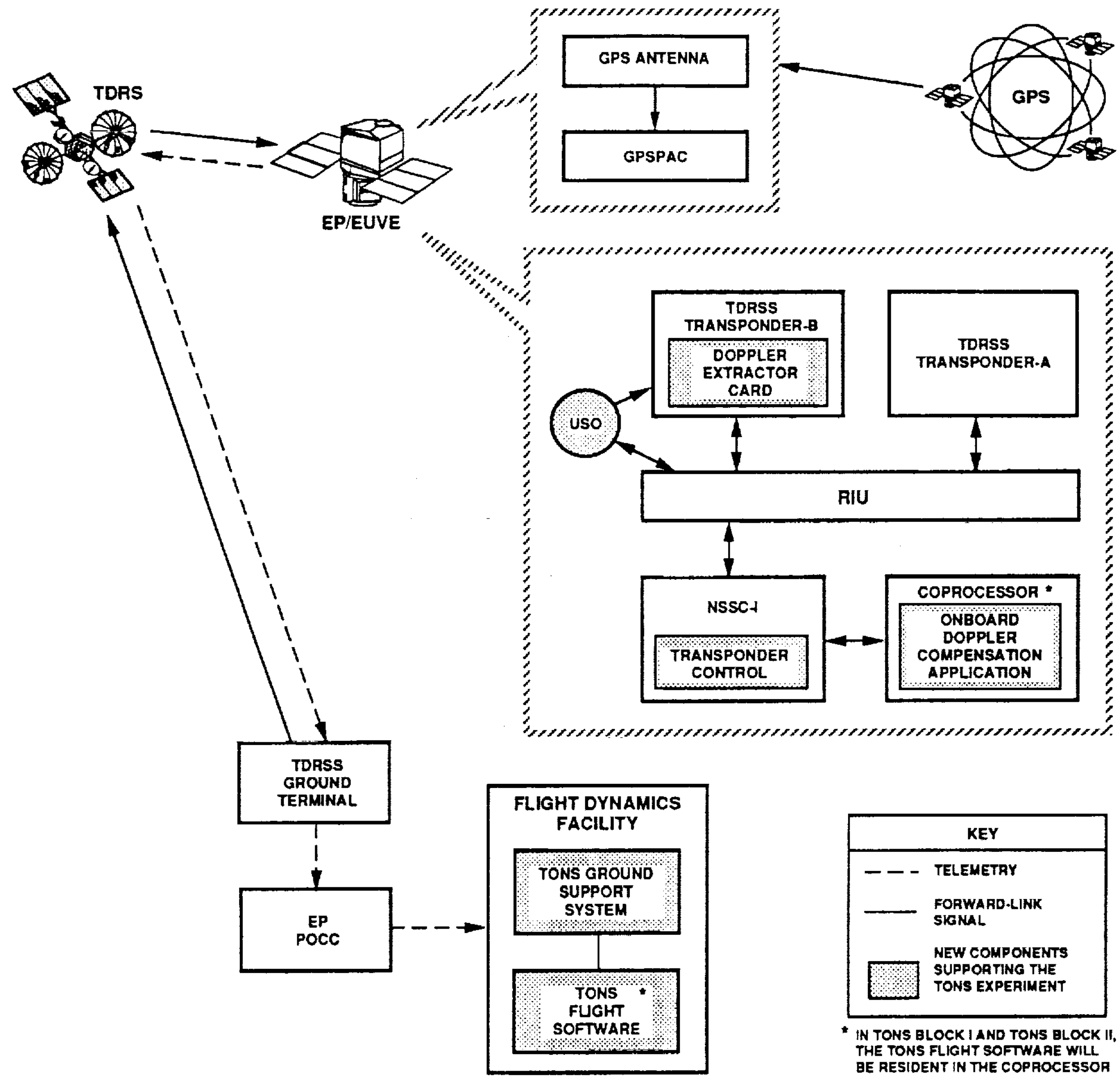

Figure 1. TONS Experiment Overview

Instead of processing the Doppler measurements onboard the EP, the Doppler count data are downlinked via the telemetry stream for ground processing. In addition, EP/EUVE will host a Global Positioning System (GPS) receiver/processor assembly unit as a secondary experiment. The downlink telemetry will also include the GPS-determined EP position, velocity, and time and other GPS engineering data.

EP/EUVE will also demonstrate OBDC and control of TDRSS forward-link signal acquisition using an OBDC application resident in the OBC coprocessor (a MIL STD 1750A architecture microprocessor) and stored commands. This process replaces the current method of signal acquisition, which requires the ground terminal to dynamically compensate the forward-link signal to eliminate the Doppler shift and requires the spacecraft control center to

request that this frequency variation be inhibited when acquisition is verified before a tracking service can be initiated.

2.2 GROUND SEGMENT

To support the TONS experiment, the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) is developing the TONS Ground Support System (TGSS) and the operational TONS Flight Software. The TGSS will extract embedded TONS data from the EP telemetry, simulate the realtime onboard processing environment, assess the quality of Doppler data downlinked from the EP, and compare EP orbit estimates derived via TONS processing with GSFC Flight Dynamics Facility (FDF) definitive (two-way) processing and with the GPS-derived EP ephemeris.The design for the TGSS is presented in Reference 5. The TGSS executes in the multiprocessor environment shown in Figure 2. The institutional FDF National Advanced Systems (NAS) and Digital Equipment Corporation (DEC) VAX processors are used to perform all TGSS support functions except for onboard environment simulation. The onboard environment simulation preparation and control functions are being developed in FORTRAN on a MicroVAX 3100. The realtime interface between the spacecraft's NSSC-I computer and the TDRSS user transponder is simulated using software developed in FORTRAN on a DEC 80286 personal computer (PC), which interfaces with the onboard computer via a MIL STD 1553B communications link.

3. FLIGHT SOFTWARE DESCRIPTION

The TONS Flight Software schedules and executes navigation processing tasks, which consist of state vector estimation and propagation, covariance computation, and Doppler compensation prediction. State vector estimation is performed once for each Doppler measurement that is processed, with the option to sample the data and process less frequently. Doppler compensation prediction is performed prior to the tracking contact to generate input FCWs based on the predicted EP state vectors. The operational TONS Flight Software is being developed for execution in the MIL STD 1750A onboard coprocessor and operates under the coprocessor flight executive software being flown on EP/EUVE.

The navigation algorithms selected for implementation in TONS are based on the following goals:

- Accuracy sufficient to provide a definitive ephemeris accuracy of 10 meters (1 σ), with continuous tracking of low Earth-orbiting spacecraft
- A maximum of 256K bytes for the navigation processing
- Efficiency, consuming no more than 20 percent of the available central processing unit (CPU) of a 15 megahertz MIL STD 1750A microprocessor
- Operational simplicity
- Ease of adaptability to the continuous beacon tracking environment
- Enhanced autonomy in the continuous beacon tracking environment

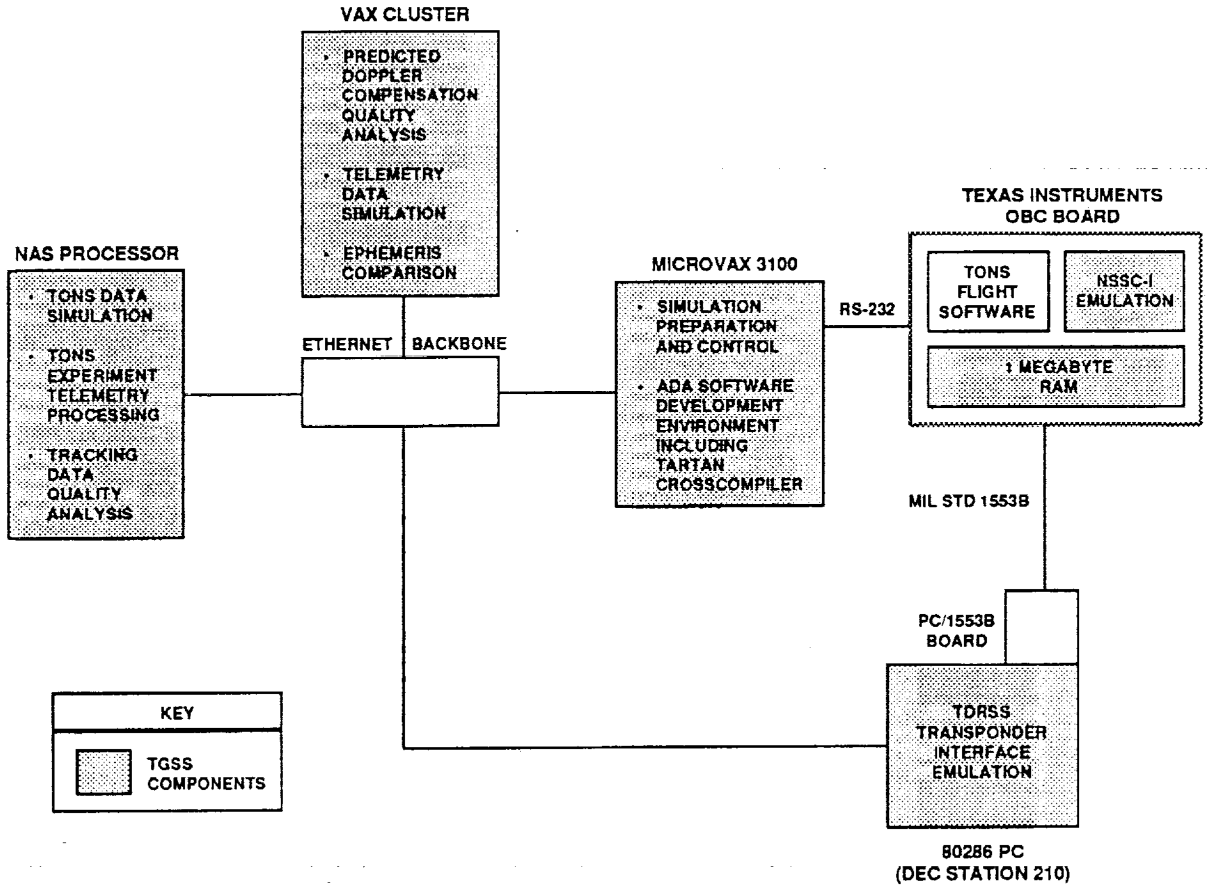

Figure 2. TGSS/Flight Software Configuration

A sequential estimation algorithm was selected over a batch least-squares algorithm because of its computational efficiency, high accuracy, lower memory requirements, and ease of adaptability to the beacon tracking environment. To enhance the performance of the estimator, a physically connected gravity process noise model, which has been adapted from the models given in References 8 and 9, is used in the user state covariance prediction; Gauss-Markov noise models are used for the other estimated parameters, which include corrections to the atmospheric drag coefficient and reference USO frequency bias and drift. Lunar and solar ephemerides, coordinate transformation matrices, and atmospheric density are computed analytically (References 10, 11, and 12). The TDRS ephemerides are computed on the ground and provided as input to the navigation processor. In a TDRSS beacon tracking environment, this information will be included in the beacon signal navigation message.

Table 1 lists the baseline set of TONS Block I navigation algorithms. These algorithms are defined in detail in Reference 13.

Table 1. Summary of TONS Block I Algorithms

ALGORITHM TYPE	ALGORITHM
PRIMARY COORDINATE SYSTEM	MEAN EQUATOR AND EQUINOX OF J2000.0 WITH ANALYTIC COORDINATE TRANSFORMATIONS
PRIMARY TIME SYSTEM	COORDINATED UNIVERSAL TIME (UTC) WITH POLYNOMIAL COEFFICIENTS UPLINKED FOR UTC-TO-UT1 COMPUTATION (UT1 = UNIVERSAL TIME CORRECTED FOR POLAR MOTION)
NUMERICAL INTEGRATOR	RUNGE-KUTTA 3(4+) FOR EP AND THE TDRS STATES AND VARIATIONAL EQUATIONS
EP ACCELERATION MODEL	• 30 x 30 NONSPHERICAL GEOPOTENTIAL [GODDARD EARTH MODEL-10B (GEM-10B)] • EARTH, SOLAR, AND LUNAR POINT-MASSES, WITH ANALYTIC EPHEMERIS • ANALYTIC REPRESENTATION OF THE HARRIS-PRIESTER ATMOSPHERIC DENSITY FOR DRAG
TDRS ACCELERATION MODEL	• 8 x 8 NONSPHERICAL GEOPOTENTIAL • EARTH, SOLAR, AND LUNAR POINT-MASSES, WITH ANALYTIC EPHEMERIS • SOLAR RADIATION PRESSURE
EP PARTIAL DERIVATIVES	NUMERICAL INTEGRATION OF VARIATIONAL EQUATIONS, INCLUDING J_2, J_3, J_4, AND ATMOSPHERIC DRAG
ESTIMATOR	EXTENDED KALMAN FILTER WITH PHYSICALLY CONNECTED PROCESS NOISE MODELS
ESTIMATION STATE	EP POSITION AND VELOCITY VECTORS; ATMOSPHERIC DRAG COEFFICIENT CORRECTION, CLOCK BIAS CORRECTION, AND FREQUENCY OFFSET AND DRIFT CORRECTIONS
MEASUREMENT MODEL	TDRSS ONE-WAY DOPPLER WITH ITERATED LIGHT-TIME SOLUTION, RELATIVISTIC CORRECTION, AND OPTIONAL FREQUENCY OFFSET AND DRIFT CORRECTIONS

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4. NAVIGATION ANALYSIS METHOD

In parallel with the development of the TONS Flight Software, a preliminary navigation accuracy analysis is being performed. This analysis has three major objectives: (1) assessment of the expected accuracy under nominal operational conditions for the TONS experiment; (2) evaluation of the sensitivity of the navigation accuracy to tracking schedule variations, dynamic modeling errors, and measurement errors; and (3) optimization of the estimation algorithm to reduce the associated error contributions. When the TONS Flight Software is available on the target platform, its operational accuracy and throughput characteristics will be determined, and optimization of the estimation algorithms to improve performance will be performed, if required.

The analysis process consists of the processing of "realistic" simulated tracking data using a sequential estimation algorithm. Accuracy is determined by comparing estimated parameters against the "truth" parameters from which the tracking data are derived.

Truth ephemerides are generated for EP/EUVE and two TDRSs using the force modeling parameters listed in Table 2. The nominal EP/EUVE orbit is circular, with an inclination of

28.5 degrees and a mean altitude of 525 kilometers. The TDRS-East and TDRS-West orbits are circular, geosynchronous, and near-equatorial, located at 41 degrees and 171 degrees west longitude, respectively.

Table 2. Truth Ephemeris Model Parameters

PARAMETER	EP/EUVE	TDRS-EAST	TDRS-WEST
ATMOSPHERIC DRAG COEFFICIENT	2.0	N/A	N/A
SOLAR RADIATION PRESSURE COEFFICIENT	1.2	1.5	1.5
GRAVITY MODEL	GEM-10B (36 x 36)	GEM-10B (12 x 12)	GEM-10B (12 x 12)
ATMOSPHERIC DRAG MODEL (F10.7 SOLAR FLUX*, POWER OF COSINE)	HARRIS-PRIESTER (250, 2)	N/A	N/A
SOLAR, LUNAR EPHEMERIDES	JPL DE-118	JPL DE-118	JPL DE-118

NOTE: GEM = GODDARD EARTH MODEL
JPL = JET PROPULSION LABORATORY
DE = DEVELOPMENT EPHEMERIS

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*UNITS = 10^{-22} WATTS/METER^2/HERTZ

These truth ephemerides are input to the Tracking Data Simulation Program of the Navigation Processing System (NPS) to simulate "realistic" one-way forward-link Doppler tracking measurements. NPS is a version of the Research and Development version of the Goddard Trajectory Determination System (R&DGTDS) upgraded by Stanford Telecommunications, Incorporated, to include the capability to simulate one-way forward-link Doppler measurements using a linear model for the USO frequency (Reference 14). Table 3 lists the preliminary operational USO frequency and tracking model error parameters used in the tracking data simulation. The USO frequency model parameters are based on the performance of the USO as determined in the COBE navigational experiment discussed in Reference 1.

Table 3. Preliminary Operational Tracking Data Simulation Parameters

PARAMETER	VALUE
USO FREQUENCY BIAS	-240 HERTZ
USO FREQUENCY DRIFT	-0.09603 HERTZ PER DAY
DOPPLER NOISE (1σ)	7 MILLIHERTZ
DOPPLER COUNT INTERVAL	10.24 SECONDS
TIMETAG OFFSET	0.0

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The TDRS-East and TDRS-West ephemerides that are used in the filter processing are created so as to produce predicted ephemerides that are representative of 1-day predictions generated based on operationally determined TDRS orbit solutions. The amplitude of the ephemeris errors is based on an analysis using the operationally determined TDRS vectors. The TDRS-East ephemeris has a maximum error of 42 meters, and the TDRS-West ephemeris has a maximum error of 64 meters. Figure 3 is an example of a 2-day comparison between these 1-day predicted ephemerides and the truth ephemerides. This comparison shows that there is a discontinuity at the day boundary, resulting from the fact that the 1-day predicted ephemerides are based on independent daily operational TDRS orbit solutions which are not constrained to be continuous at the day boundary.

The simulated tracking data are processed in the NPS Filter Program. The NPS Filter Program is used in this preliminary navigation analysis because the TONS Flight Software will not be available earlier than September 1991. The NPS Filter Program includes the majority of the TONS Flight Software algorithms (e.g., physically connected gravity state process noise model, 30 x 30 geopotential model, estimation of USO frequency bias and drift corrections) but does not currently include the Gauss-Markov noise models, the analytic solar/lunar ephemerides, and the analytic atmospheric drag model. Table 4 lists the nominal values for the a priori offsets in the parameters to be estimated; Table 5 lists the nominal TONS force model, a priori variances, and filter parameters.

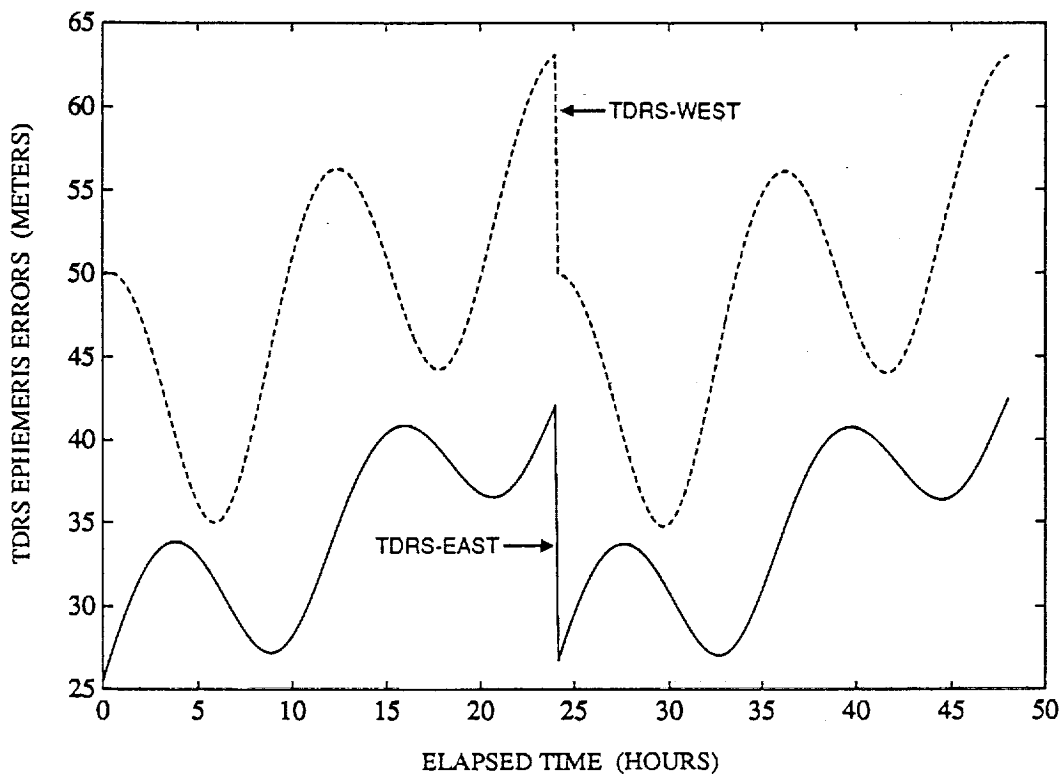

Figure 3. TDRS Ephemeris Errors

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Table 4. A Priori Offsets in Parameters

ESTIMATED PARAMETER	A PRIORI OFFSET FROM TRUTH
EP POSITION VECTOR	500 METERS (RSS)
EP VELOCITY VECTOR	0.1 METERS/SECOND (RSS)
ATMOSPHERIC DRAG COEFFICIENT	10 PERCENT
USO FREQUENCY BIAS	8.3 HERTZ
USO FREQUENCY DRIFT	0.0093 HERTZ/DAY

NOTE: RSS = ROOT SUM SQUARE

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Table 5. TONS Nominal Force Model and Filter Parameters

PARAMETER	VALUE
EP GRAVITY MODEL	GEM-10B (30 x 30)
ATMOSPHERIC DRAG MODEL (F10.7 SOLAR FLUX, POWER OF COSINE)	HARRIS-PRIESTER (250, 2)
INITIAL EP POSITION VARIANCE (KILOMETERS^2)	10, 10, 10
INITIAL EP VELOCITY VARIANCE (METERS^2/SECOND)	9, 9, 9
DOPPLER MEASUREMENT STANDARD DEVIATION (MILLIHERTZ)	50
USO FREQUENCY BIAS INITIAL STANDARD DEVIATION (HERTZ)	252.77
USO FREQUENCY DRIFT INITIAL STANDARD DEVIATION (HERTZ/DAY)	0.1053
DRAG CORRECTION VARIANCE	1.0
CONSTANT RATE VELOCITY PROCESS NOISE (KILOMETERS^2/SECOND^2/SECOND)	10^{-16}
USO FREQUENCY BIAS PROCESS NOISE RATE	0.0
USO FREQUENCY DRIFT PROCESS NOISE RATE (HERTZ^2/DAY^2/SECOND)	3.3×10^{-6}
DRAG CORRECTION PROCESS NOISE RATE (SECONDS^{-1})	10^{-5}

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There are three different spacecraft state process noise models available in the NPS. A symbol Q is commonly used to denote the process noise covariance matrix. The constant rate model assumes that the process noise matrix is diagonal, with elements that grow linearly with time. When this model is used, a set of constant growth rate parameters, one for each diagonal element, must be specified. The adaptive rate model is similar to the constant rate model, except that the growth rate parameters are adaptively adjusted during the filter processing according to an algorithm that monitors the behavior of the system model against that of the measurement residuals at each measurement point (Reference 14). The third model is based on the formulation known as the physically connected gravity process noise model (References 8 and 9). In the subsequent discussion, these three process noise models will be referred to as the constant rate (CQ), adaptive rate (AQ), and the physically connected gravity (GQ) process noise models, respectively. In applying the CQ and AQ models to the current analysis, only the velocity variances are assumed to be nonzero. Table 5 lists the nominal values for the CQ velocity, USO frequency bias, USO frequency drift, and drag coefficient correction process noise rates. The AQ algorithm requires two growth rate parameters. The AQ results presented below were obtained using the same values as those given in Table 5 for the velocity process noise rates for both parameters, such that the AQ model is nearly identical to the CQ model.

When the TONS Flight Software is available, the major conclusions of this analysis will be verified using the operational software. In addition, further analysis will be performed to investigate the expected accuracy of the TONS estimation algorithms as a function of the additional algorithm tuning parameters (e.g., Gauss-Markov process noise parameters) and to investigate the throughput characteristics of the Flight Software.

5. NAVIGATION ACCURACY ANALYSIS

The navigation accuracy analysis was performed using the simulated tracking data and sequential orbit determination procedures described above. An orbit determination process requires two basic sets of input data: a set of tracking measurements and a set of parameters for the filter processing. The navigation accuracy results presented in this section were obtained using a number of different input data sets. To study the sensitivity of the filter solutions to various error sources and different tracking scenarios, both the tracking measurement set and filter processing control parameters were varied. In particular, these input data sets were prepared to examine the sensitivity of the orbit determination accuracies to the following:

- Tracking scenarios
- Dynamic and local errors, including
  - Geopotential modeling errors
  - TDRS ephemeris errors
  - Atmospheric drag modeling errors
  - Measurement noise
  - USO frequency bias and drift

5.1 SENSITIVITY TO TRACKING SCENARIOS

The sensitivity of navigation accuracy to different tracking scenarios was studied using nominal simulated tracking data (Table 3) and nominal filter processing control parameter values (Tables 4 and 5 and Figure 3). The minimum tracking schedule for the EP/EUVE mission consists of one 5-minute pass of one-way forward-link tracking per orbit; however, in the TONS Block II beacon tracking mode, near-continuous forward-link tracking may be obtained. Tracking data were simulated for the following three scenarios:

- Two-day nominal tracking with an even distribution: one 5-minute tracking contact every EP/EUVE orbit from alternating TDRSs, with a relatively even spacing between contacts (approximately 100 minutes), one measurement every 10.24 seconds
- Two-day nominal tracking with an uneven distribution: one 5-minute tracking contact every EP/EUVE orbit from alternating TDRSs, with several large gaps between contacts (up to 185 minutes), one measurement every 10.24 seconds
- Two-day near-continuous tracking: tracking from each TDRS whenever it is visible, one measurement every 30.72 seconds

Figures 4 and 5 show the total root-sum-square (RSS) position differences between the truth ephemeris and the filter solutions obtained incorporating the TDRS ephemeris errors previously defined and using the GQ process noise model for the nominal and near-continuous tracking scenarios, respectively. After a transient period, each solution appears to reach a steady state. The length of this transient period decreases from approximately 16 hours for the nominal tracking scenarios to 1 hour for the near-continuous tracking scenario.

The accuracy of the steady-state solution obtained using the nominal tracking scenarios is seen to be below 50 and 70 meters in total position for the even and uneven distributions, respectively. This accuracy improves to approximately 12 meters for the near-continuous scenario.

Similar solutions were obtained using the CQ and AQ process noise model options. Figure 6 shows the total EP position error in the solution computed using the CQ and AQ process noise models for the nominal tracking scenario, with the even data distribution. However, the magnitude of the steady-state filter covariance in the two cases is significantly different, particularly for the nominal tracking scenario. The RSS position standard deviation associated with the covariance computed using the GQ process noise model varies between 15 and 200 meters, whereas the corresponding standard deviation associated with the covariance computed using the AQ process noise model varies between 15 and 60 meters. The maximum standard deviation obtained using the GQ process noise model is significantly larger than the observed solution error; the maximum value occurs at the end of the propagation period between tracking contacts and is proportional to the length of the propagation. The effective variance growth rate of the GQ model appears to be significantly larger than the process noise rate used in the CQ and AQ models. Further analysis indicates that the behavior of the covariance computed using the GQ model is consistent with that computed using a constant velocity rate of 10^{-14} [(kilometers/second)^2/second]. This overestimate of the covariance may arise

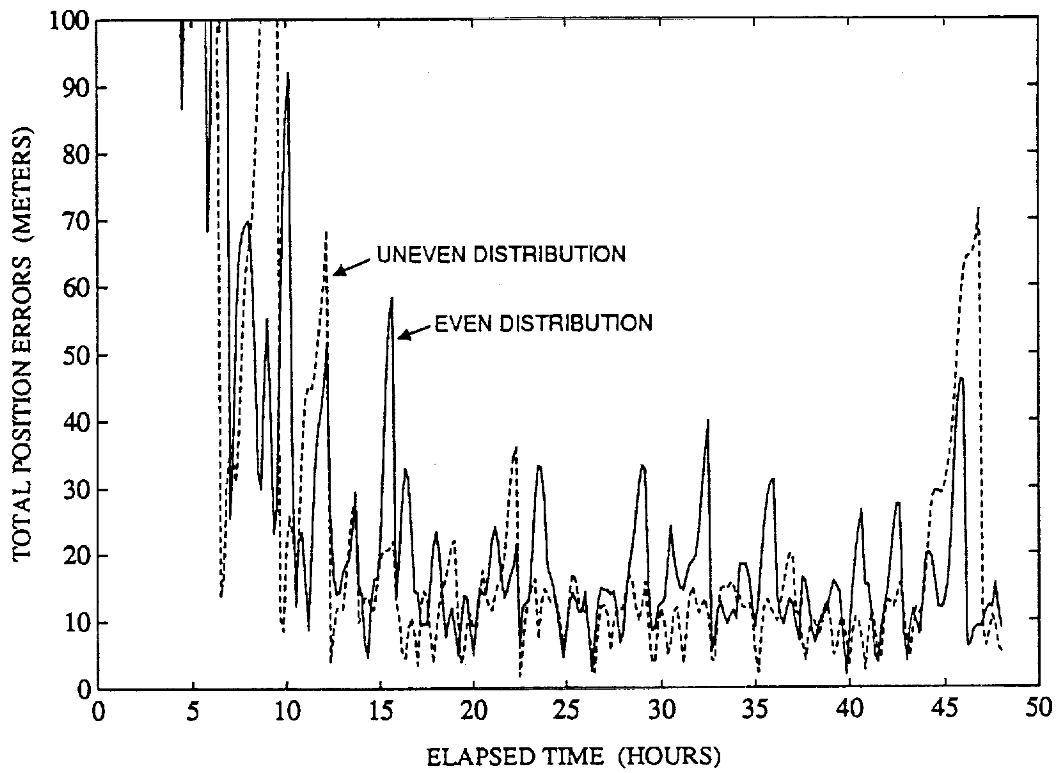

Figure 4. **Total EP Position Error Using the Nominal Tracking Scenario With GQ Process Noise**

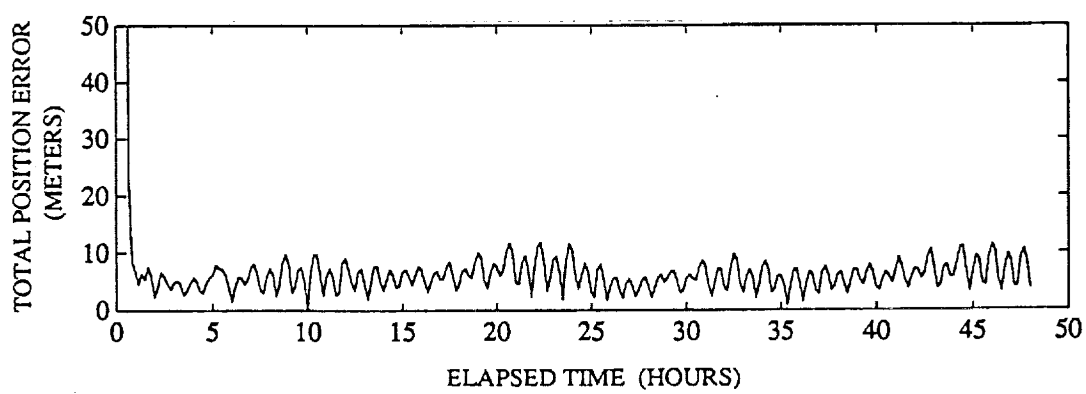

Figure 5. **Total EP Position Error Using the Near-Continuous Tracking Scenario With GQ Process Noise**

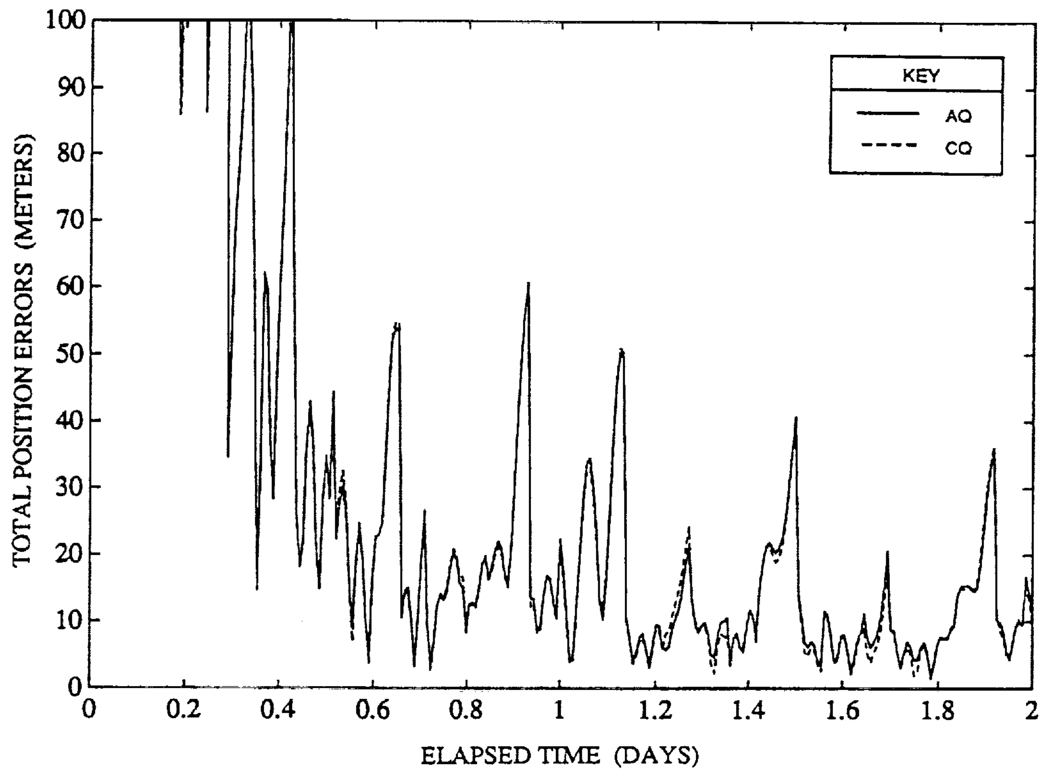

Figure 6. Total EP Position Error Using the Nominal Tracking Scenario With CQ and AQ Process Noise Models

from the fact that the GQ model computes the gravity process noise associated with omission of the gravitational harmonics between orders 30 and 50, whereas the tracking data are simulated using a geopotential model of order 36. The reason for this difference remains under study.

To study the stability of the filter performance over an extended period of time, 18-day solutions were generated using the nominal tracking scenario with an even data distribution. The 18-day TDRS error models were constructed by repeating 2-day error models. These 2-day models represent the 2-day prediction errors for the TDRS ephemerides and are similar in structure to those shown in Figure 3, which model the expected daily upload of 1-day predictions. Thus the predicted TDRS-East and TDRS-West ephemerides used for the 18-day filter solutions have a piece-wise continuous structure with 9 continuous sections, each 2 days long. All other input parameters for the filter processing were the same as those used in the 2-day solutions discussed above. Figures 7 and 8 show the resultant errors in the filter solutions using the GQ and AQ process noise models, respectively. The solution error for the GQ case remains at a maximum of 50 meters after 18 days of processing, and the solution error for the AQ case remains at a 45-meter level, with mean errors of 11.08 and 11.17 meters, respectively.

In the case of nonstate estimated parameters [drag coefficient correction parameter, USO frequency bias (b_0), and USO frequency drift (b_1)], the steady-state solutions fluctuate about

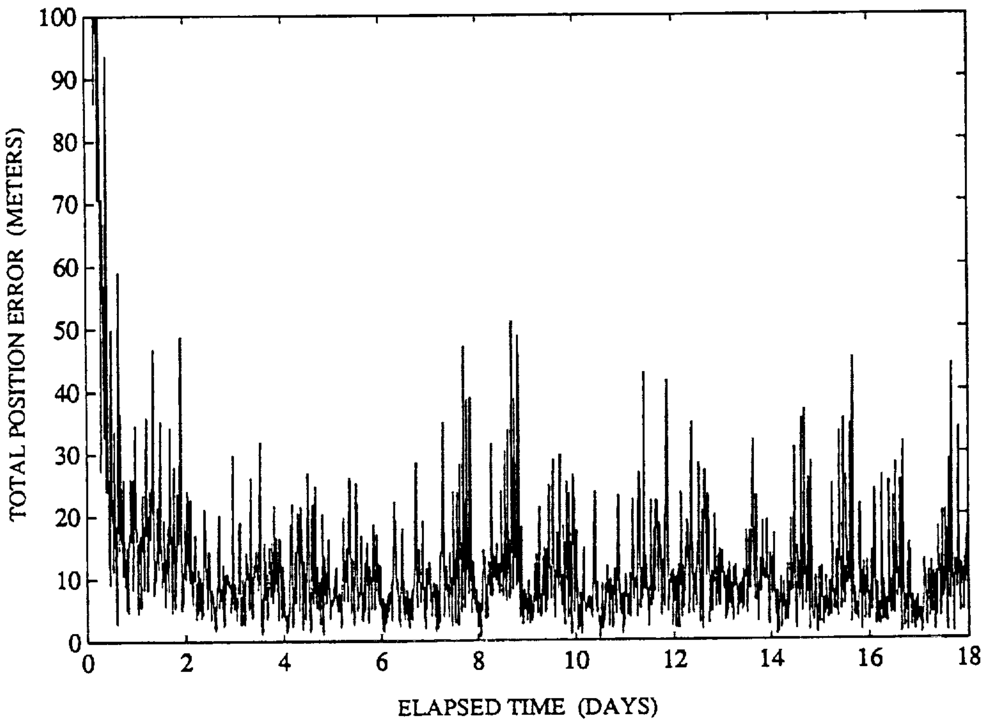

Figure 7. Total EP Position Error Using the GQ Process Noise Model

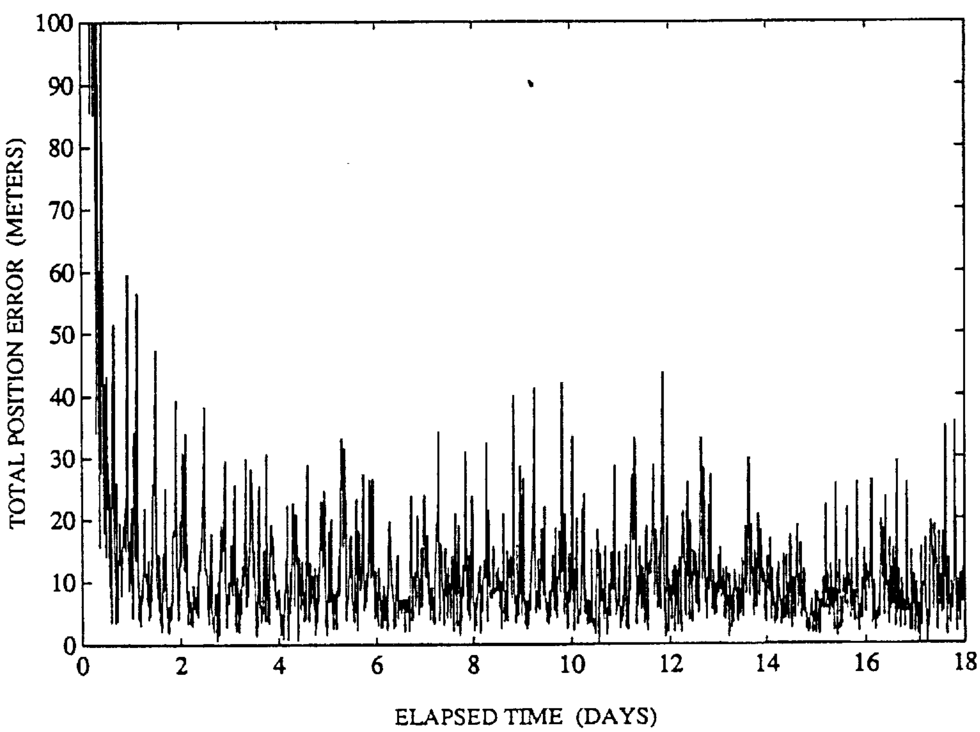

Figure 8. Total EP Position Error Using the AQ Process Noise Model

the true values. In the case of the drag correction coefficient, the mean and standard deviation of the steady state solutions are –0.02 and 0.05 for the nominal tracking scenario and –0.005 and 0.05 for the near-continuous tracking scenario, where the true value is 0.0, since the nominal and truth drag models were identical except for an initial scale factor offset. The instantaneous USO frequency bias estimates also follow the truth total bias. Figure 9 shows that the estimated USO frequency bias for the continuous case nearly reproduces the true total bias with a maximum error of 0.0107 hertz (5 parts in 10^{12}) and a mean error of 0.001 hertz after 1 hour of processing. The estimated bias for the nominal tracking case shown in Figure 10 exhibits an initial deviation from the truth but eventually converges to the correct value with a maximum steady-state error of 0.077 hertz (4 parts in 10^{11}) and a mean error of 0.004 hertz.

5.2 SENSITIVITY TO DYNAMIC AND LOCAL ERRORS

Dynamic and local error sources that commonly degrade orbit estimation accuracy are the following:

- USO frequency bias and drift
- Atmospheric drag modeling errors
- Geopotential modeling errors
- TDRS ephemeris errors
- Doppler measurement noise
- Measurement timetag errors

Corrections to the atmospheric drag coefficient, USO frequency bias, and USO frequency drift can be estimated in the orbit determination process to reduce the magnitude of the associated errors. Therefore, it is important to examine the accuracy with which the proposed estimation algorithm can determine these parameters for a given tracking scenario. Accurate estimation of the USO frequency corrections was already addressed. However, in the case of the atmospheric drag coefficient correction, the same Harris-Priester atmospheric density table [solar flux level (F10.7) = 250] and model [power of the cosine term (N) = 2] was used in both the truth and filter processing, with only a small initial offset impacting the filter processing.

To provide a more realistic test, different atmospheric models were used in the truth and filter processing for the nominal tracking scenario. Figure 11 shows the variation in the estimated drag coefficient corrections obtained using the Harris-Priester models associated with (1) F10.7 = 250, N = 6; (2) F10.7 = 225, N = 2; and (3) F10.7 = 225, N=6 in the filter processing as compared with the nominal case using F10.7 = 250, N=2. These results illustrate that the filter was able to readjust the correction values to reflect the changes in the atmospheric densities brought about by modeling errors. The position accuracy associated with these cases was found to be comparable to that obtained in the nominal case discussed earlier.

Table 6 lists the maximum contributions to the steady-state orbit determination errors over a 2-day arc from the remaining error sources that were studied. The impact of measurement timetag errors remains under study.

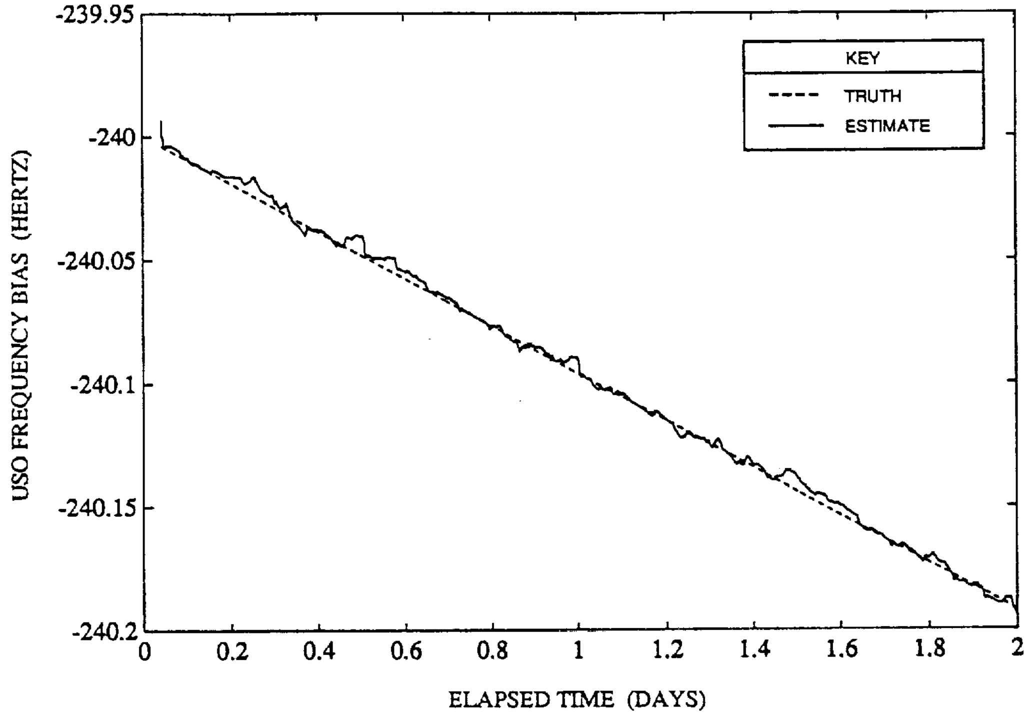

Figure 9. **USO Frequency Bias Estimate for the Near-Continuous Tracking Scenario**

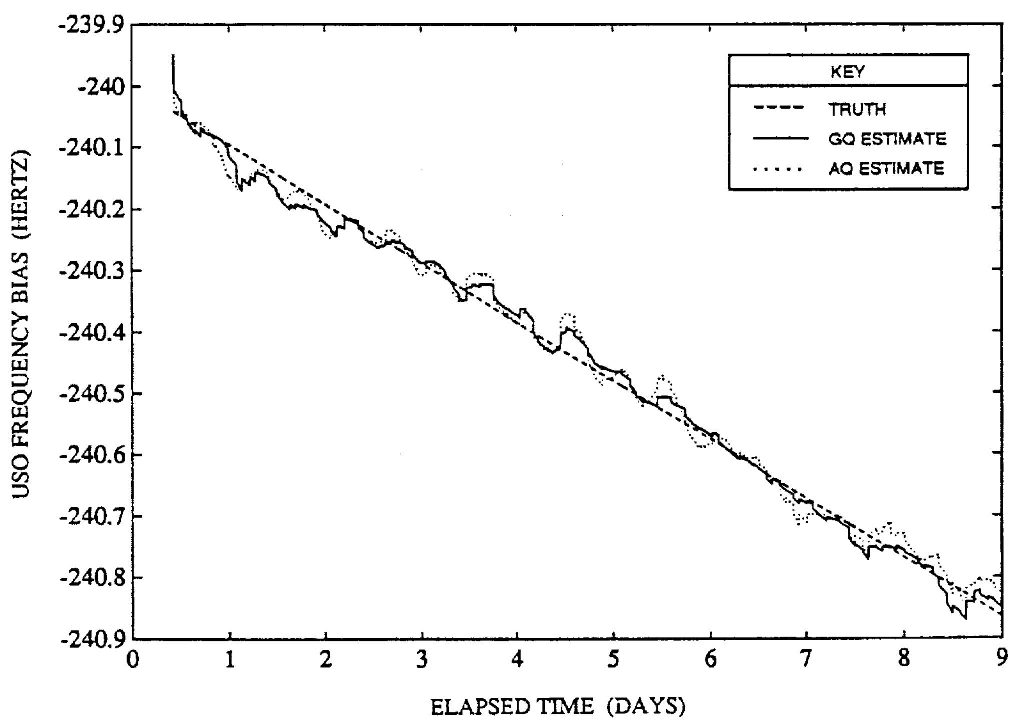

Figure 10. **USO Frequency Bias Estimate for the Nominal Tracking Scenario**

6130-2

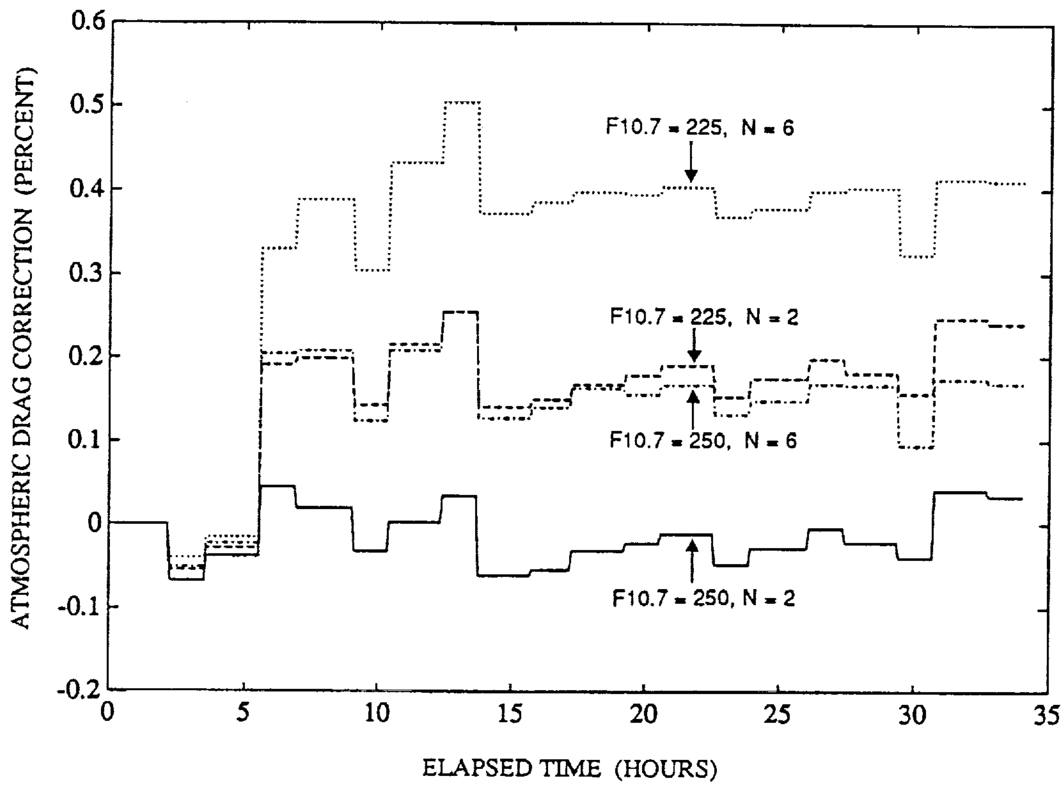

Figure 11. Variation in the Estimated Atmospheric Drag Correction

Table 6. Maximum Contributions to Steady-State Orbit Determination Errors

ERROR SOURCE	MAXIMUM RSS POSITION ERROR CONTRIBUTION (METERS)	
	NOMINAL TRACKING	NEAR-CONTINUOUS TRACKING
GEM-10B (30 x 30)	20	5
GEM-10B (15 x 15)	120	20
TDRS EPHEMERIS ($\approx$ 50 METERS)	10	10
DOPPLER NOISE (7 MILLIHERTZ)	20	<1
DOPPLER NOISE (35 MILLIHERTZ)	30	<1

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Among these error sources, the nonspherical gravity errors were found to have the strongest influence on the orbit determination accuracy. The orbit determination errors due to the gravity model errors depend on the model and its size used in the filter solutions. Figure 12 shows the total EP position error for the nominal tracking scenario using a 15 x 15 geopotential in place of the baseline GEM-10B 30 x 30 model. Because the tracking data were generated using a GEM-10B 36 x 36 geopotential model, the true contribution from geopotential modeling errors is expected to be larger than that shown in Table 6. The magnitude of the geopotential error contribution remains under study.

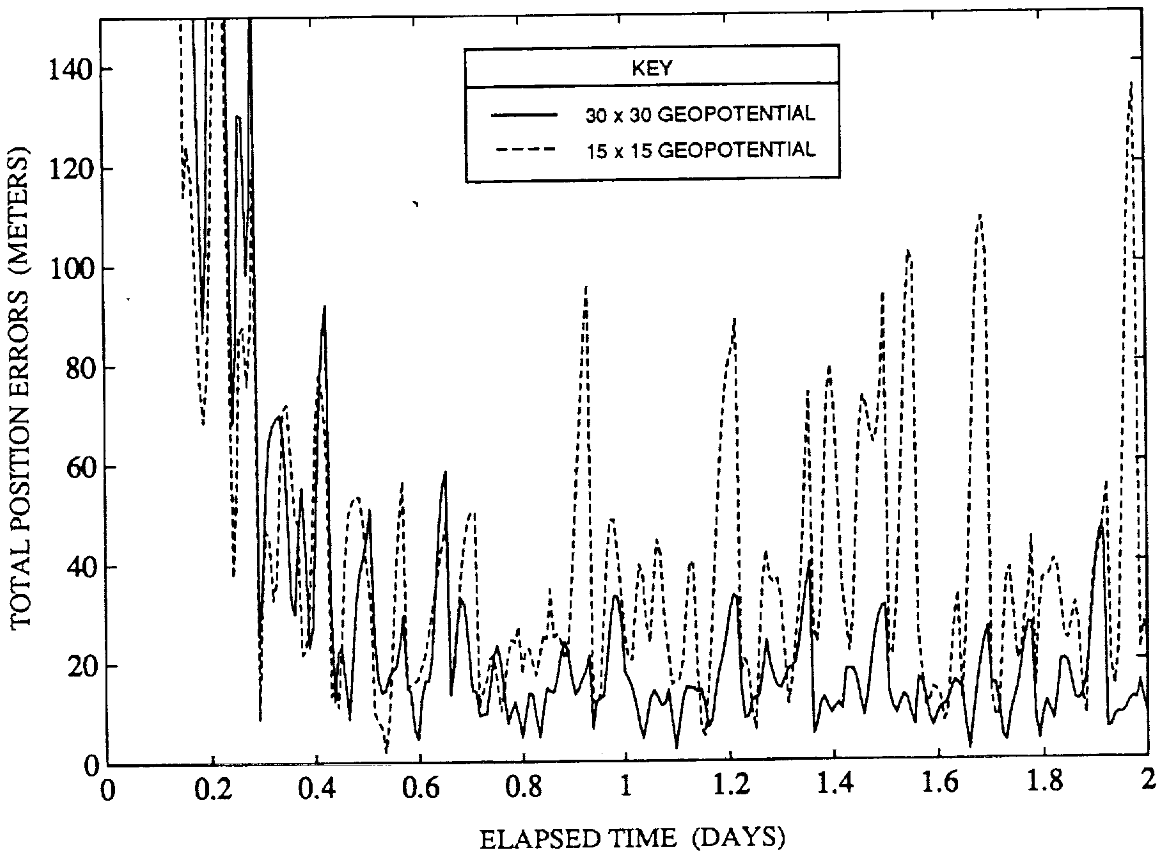

Figure 12. Comparison of Total EP Position Error Using the Nominal Tracking Scenario With GQ Process Noise Using a 15 x 15 Geopotential Model Versus a 30 x 30 Geopotential Model

The error contribution from TDRS ephemeris errors was determined by processing nominal tracking data using TDRS ephemerides with and without ephemeris errors in the filter processing. The impact of TDRS ephemeris errors associated with 1-day predictions based on operational solutions is not very significant.

The error contribution from measurement noise was evaluated by processing tracking data simulated with and without Doppler measurement noise. The values for the observation standard deviation used in the filter processing were approximately 7 times the noise standard

deviation used in tracking data simulation. The measurement noise contribution is significant for the nominal tracking scenario but is insignificant in the near-continuous tracking scenario.

6. REMARKS

The navigation analysis results presented in the previous section are based on a preliminary operational error model and are limited by the data simulation and sequential estimation capabilities available at the time of the study. Further analysis is planned using a more refined operational error model as additional data simulation and sequential estimation capabilities become available.

The impact of Doppler measurement timetag errors on the TONS experiment navigation accuracy are being evaluated. Data simulation using realistic timetag offsets has begun, and a thorough analysis is in progress. If the errors due to poorly known timetag offsets are found to be significant, their impact can be reduced by estimating a timetag offset parameter modeled as a Gauss-Markov process. This approach will be studied using a VAX-based version of the Flight Software. The expected frequency determination accuracy will also be further investigated using the Gauss-Markov process modeling option available in the VAX-based version of the Flight Software.

The preliminary operational error model used a GEM-10B 36 x 36 geopotential model to generate the EP truth ephemeris because it was the most precise model available in NPS at the time. As soon as the capability to use the 50 x 50 GEM-T2 geopotential model is available in NPS, tracking data will be simulated using a truth ephemeris based on this model, and the impact of geopotential model errors will be reassessed. In addition, the covariance predictions obtained using the GQ process noise model will be reevalutated to determine if they are consistent with this more realistic geopotential modeling error. Additional planned navigation analysis includes a more thorough analysis of the impact on performance of the tuning parameters associated with the GQ and AQ process noise models.

7. CONCLUSIONS

The following are the major conclusions resulting from this preliminary navigation analysis for EP/EUVE:

- An orbital position accuracy of better than 50 meters (3σ) and a frequency determination accuracy of better than 0.08 hertz (4 parts in 10^{11}) (3σ) can be achieved for a nominal tracking schedule of one 5-minute contact per orbit after 16 hours of processing using the preliminary operational error models.

- An orbital position accuracy of better than 12 meters (3σ) and a frequency determination accuracy of better than 0.01 hertz (5 parts in 10^{12}) (3σ) can be achieved for a near-continuous tracking schedule after 1 hour of processing using the preliminary operational error models.

- The orbital position accuracy was found to be most sensitive to (1) reduction in the degree of the geopotential model from 30 to 15 and (2) periodic versus near-continuous tracking.
- Comparable navigation accuracy was obtained using either the physically connected gravity process noise model or properly tuned adaptive and constant rate process noise models.

Based on these results, a 30 x 30 geopotential model will be used in the TONS Flight Software, and tracking contacts longer than 5-minutes are recommended whenever possible. In addition, further study will be performed to characterize the expected Doppler measurement timetag errors as part of the EP/EUVE prelaunch testing and to evaluate their impact on the navigation accuracy.

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